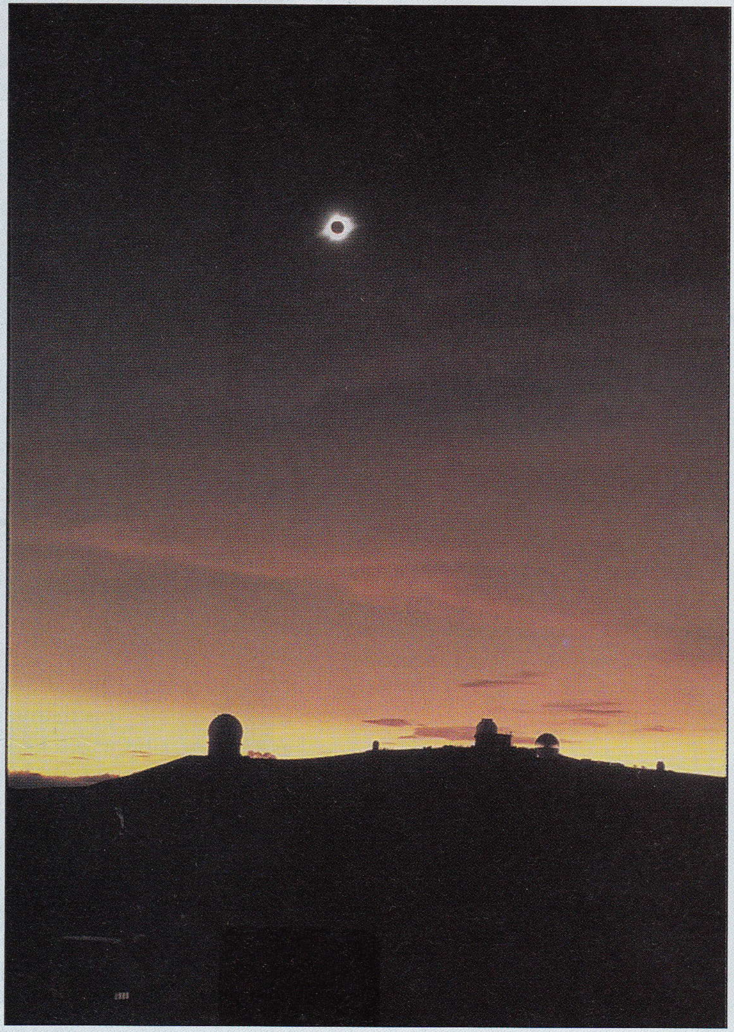
Chapter Six

6

The Moon

The Moon.
(Photo © UC Regents/Lick Observatory. Unauthorized use prohibited.)

Lunar crater.
(Courtesy of NASA.)



A total eclipse of the Sun.
(Courtesy of Richard Wainscoat.)

The Moon is our nearest neighbor in space, a natural satellite orbiting the Earth. It is the frontier of direct human exploration, an outpost that we reached more than a quarter century ago but from which we have since drawn back. But despite our retreat from its surface, the Moon remains of great interest to astronomers. Although originally the Moon was molten, its small mass and radius have made it difficult for it to either generate or retain any appreciable internal heat. It is therefore a dead world, with neither plate tectonic nor volcanic activity. That inactivity when coupled with the Moon's lack of atmosphere means that its surface features are essentially unaltered since its youth. But the Moon has not always been quiescent. Shortly after its formation, it was pelted with a hail of rocky fragments whose size ranged up to 200 kilometers (about 100 miles) in diameter. The small fragments made craters, and the big fragments made huge basins. The basins subsequently flooded with lava (long since congealed) to create several dark, nearly circular plains easily visible to the naked eye. The Earth probably once bore such features, but erosion and plate motions have erased them. On the Moon's windless, rainless, airless surface, however, they remain—a record of events in the early Solar System that gives clues not only to the Moon's birth but to that of the Solar System as well.

In this chapter, we will describe the Moon's surface and why astronomers believe so many of its features were carved by impact. We will see that lunar rocks differ significantly from terrestrial ones and how they point to the Moon's having been born in a cataclysmic event early in the Earth's history. We will also discuss how the Moon affects Earth today through tides and eclipses. But we will begin with a short physical description of the Moon to help us visualize this nearest world.

6.1 DESCRIPTION OF THE MOON

General Features

The Moon is about one-fourth the diameter of the Earth, a barren ball of rock, possessing no air, water, or life. In the words of lunar astronaut Buzz Aldrin, the Moon is a place of "magnificent desolation." But you don't have to walk on the Moon to see its desolation. Even to the naked eye, the Moon is a world of grays without the vivid colors of the terrestrial landscape. Yet even gray has its variety, as you can see where the dark roughly circular areas stand out from the lighter background,* as shown in figure 6.1.

Surface Features

Through a small telescope or even a pair of binoculars, you can see that the dark areas are smooth while the bright areas are covered with numerous large circular pits called **craters,** as illustrated in figure 6.2. Craters usually have a raised rim and range in size from tiny holes less than a centimeter across to gaping scars in the Moon's crust such as Clavius,† about 240 kilometers (150 miles) across. Some of the larger craters have mountain peaks at their center.

The large, smooth, dark areas are called **maria** (pronounced MAR-ee-a), from the Latin word for "seas." However, these regions, like the rest of the Moon, are totally devoid of water. This usage comes from early observers who believed the maria looked like oceans and who gave them poetic names such as Mare (pronounced MAR-ay) Serenitatis (Sea of Serenity) or Mare Tranquillitatis (Sea of Tranquility), the site where astronauts first landed on the Moon.

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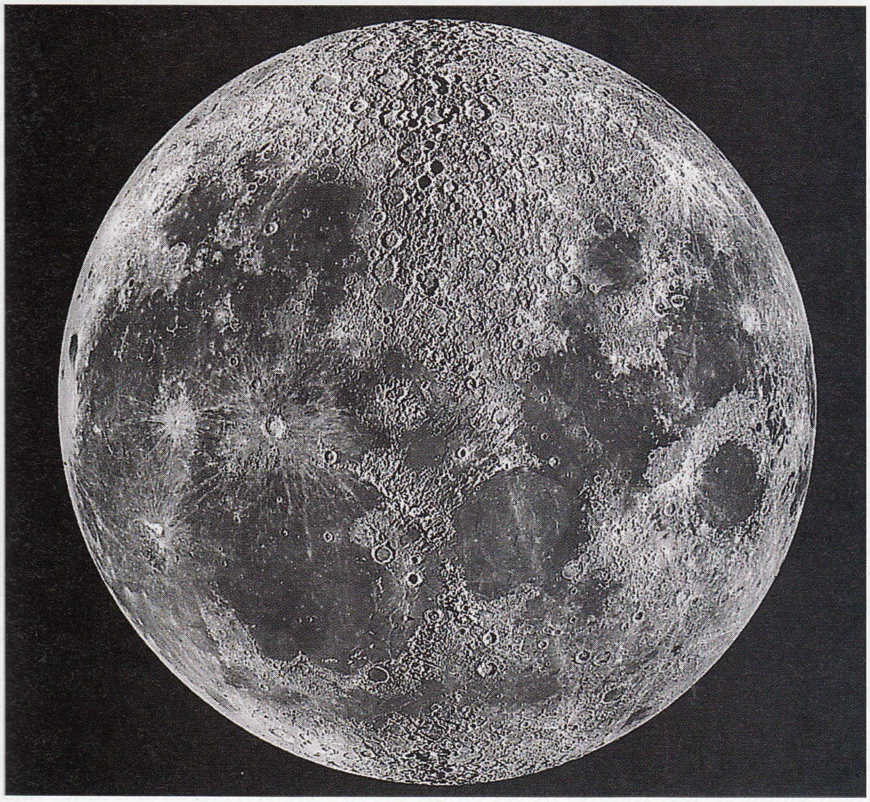
*These dark features create the face of the "Man in the Moon."

†Most lunar craters are named for famous scientists. For example, Cristoph Clavius (1537–1612) was a German astronomer and mathematician.

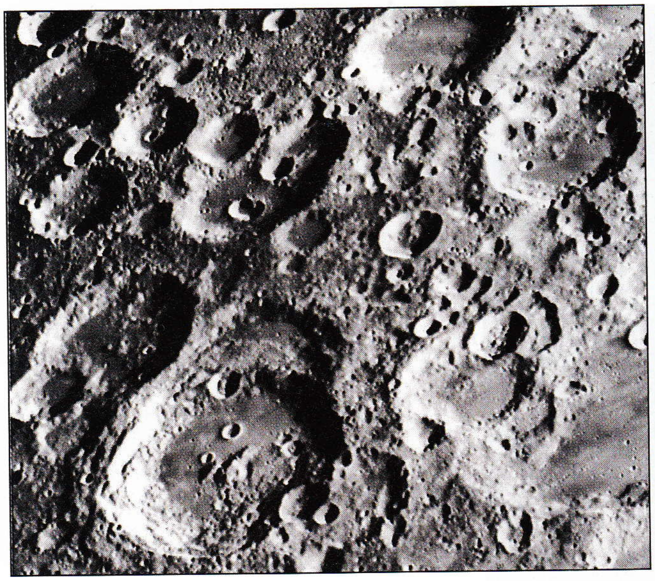
FIGURE 6.1
The Moon.
(Courtesy of Stephen E. Strom.)



Note: In this picture and several other Moon pictures in this chapter, the Moon's south pole is at the top. This shows the Moon as it looks in most astronomical telescopes because such instruments invert the image.

FIGURE 6.2
Photograph showing the different appearance of the lunar highlands and maria. The highlands are heavily cratered and rough. The maria are smooth and have few craters.
(Photo © UC Regents/Lick Observatory. Unauthorized use prohibited.)

Question: If you look very carefully at this picture you will notice something odd about the shadows around craters. How was this picture made?



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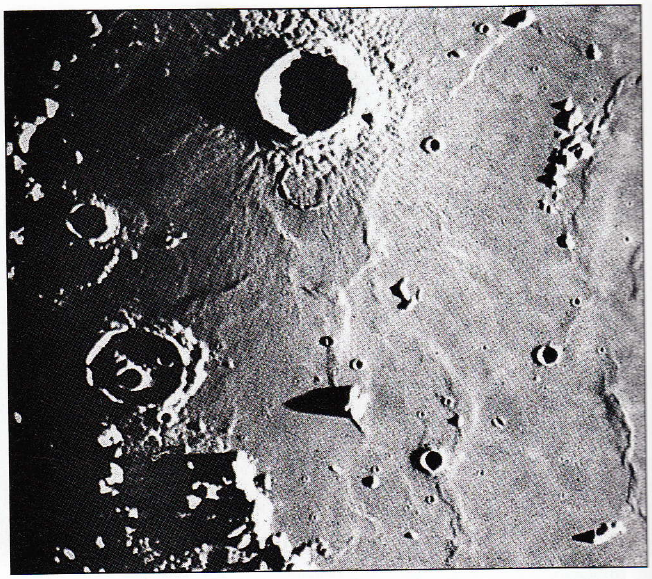


B

Question: In (A) a small crater lies at the edge of a larger one. Which formed more recently: the small one or the large one?

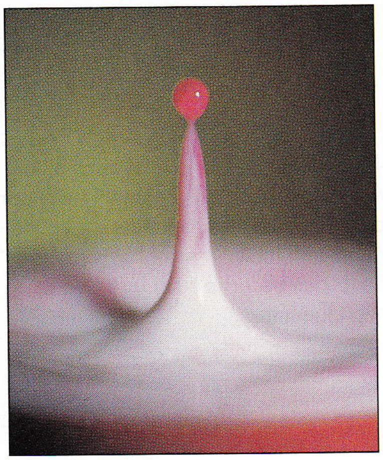
FIGURE 6.3
(A) Overlapping craters in the Moon's highlands. (B) Isolated craters in the smooth mare. (Photo © UC Regents/Lick Observatory. Unauthorized use prohibited.)

The bright areas that surround the maria are called **highlands.** The highlands and maria differ in brightness because they are composed of different rock types. The maria are basalt, a dark, congealed lava rich in iron, magnesium, and titanium silicates. The highlands, on the other hand, are mainly anorthosite, a rock type rich in calcium and aluminum silicates. This difference has been verified from rock samples obtained by astronauts. Moreover, the samples also show that the highland material is generally less dense than mare rock and considerably older.

The highlands are not only brighter and their rocks less dense than the maria, they are also more rugged, being pitted with craters. In fact, highland craters are so abundant that they often overlap, as shown in figure 6.3A. Contrast this picture with the mare region shown in figure 6.3B, in which only a few, small craters are visible.

From many craters, long, light streaks of pulverized rock called **rays** radiate outward, as shown in figure 6.4. A particularly bright set spreads out from Tycho near the Moon's south pole and can be seen easily with a pair of binoculars when the Moon is full.

A small telescope reveals still other surface features. Lunar canyons known as **rilles,** perhaps carved by ancient lava flows, wind away from some craters, as shown in figure 6.5. Elsewhere, straight rilles gouge the surface, probably the result of crustal cracking. Drying mud and chocolate pudding left too long in the refrigerator show similar cracks.



If you pour a tiny drop of cranberry juice into a glass of milk, you will see an effect similar to the one that makes lunar crater central peaks. The cranberry juice drops into the milk but is then pushed up again as the milk "rebounds," as shown in the high-speed photo above.
(The Harold E. Edgerton 1992 Trust/Palm Press, Inc.)

Origin of Lunar Surface Features

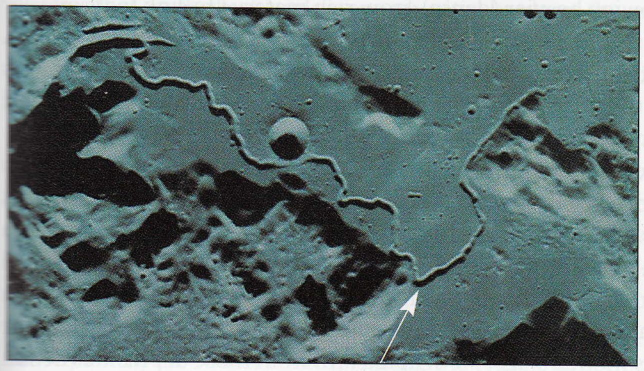
Nearly all the surface features we see on the Moon—craters, maria, and lunar rays—were made by the impact of solid bodies on its surface. When such an object hits a solid surface at high speed, it disintegrates in a cloud of vaporized rock and fragments. The resulting explosion blasts a hole whose diameter depends on the mass and velocity of the impacting object. The hole's shape is circular, however, unless the impact is grazing.

FIGURE 6.4

The long, narrow, white streaks radiating away from the crater at the top are lunar rays.
(© UC Regents; UCO/Lick Observatory image.)

Question: Can you see rays near other craters?

Question: Some rays cross maria. What does this imply about the relative age of the rays and the maria?



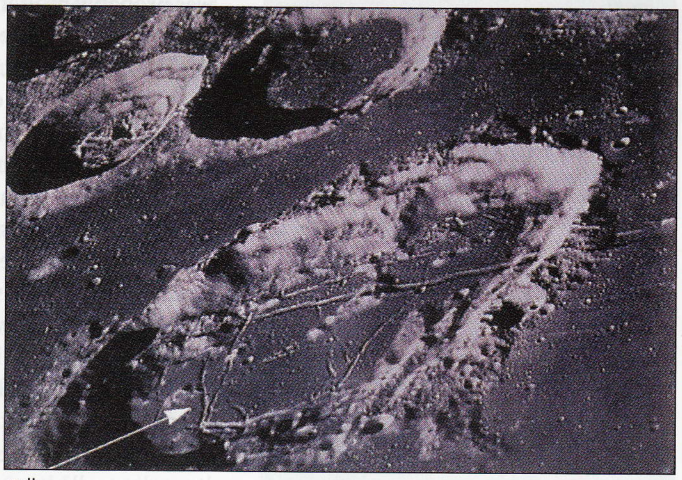


FIGURE 6.5

Photographs of some lunar rilles.
(Courtesy of NASA.)

As the vaporized rock expands from the point of impact, it forces surrounding rock outward, piling it into a raised rim. Pulverized rock spatters in all directions, forming rays. Sometimes the impact compresses the rock below the crater sufficiently that it rebounds upward, creating a central peak, as shown in figure 6.6.

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(© UC Regents; UCO/Lick Observatory image.)

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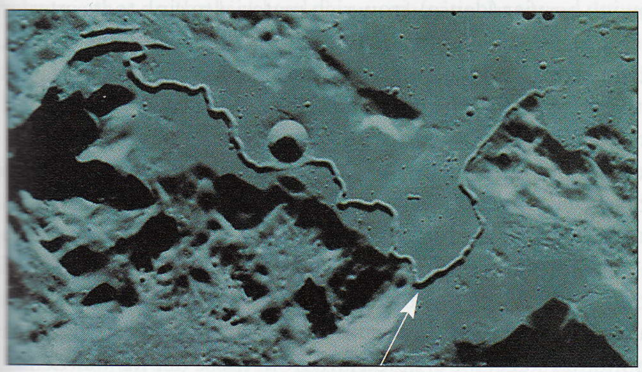

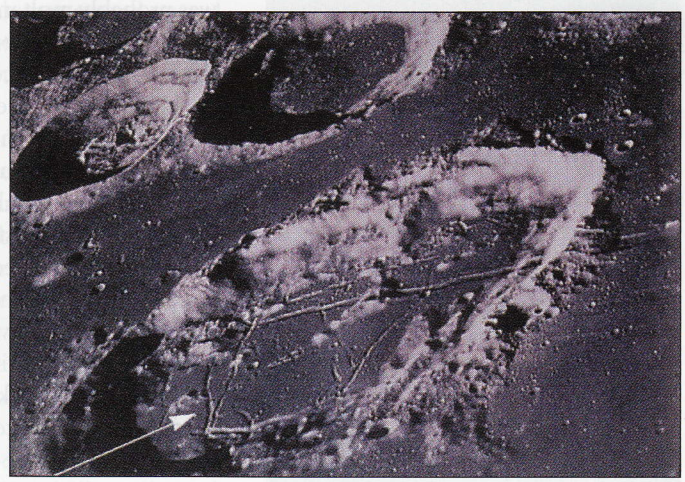

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(Courtesy of NASA.)

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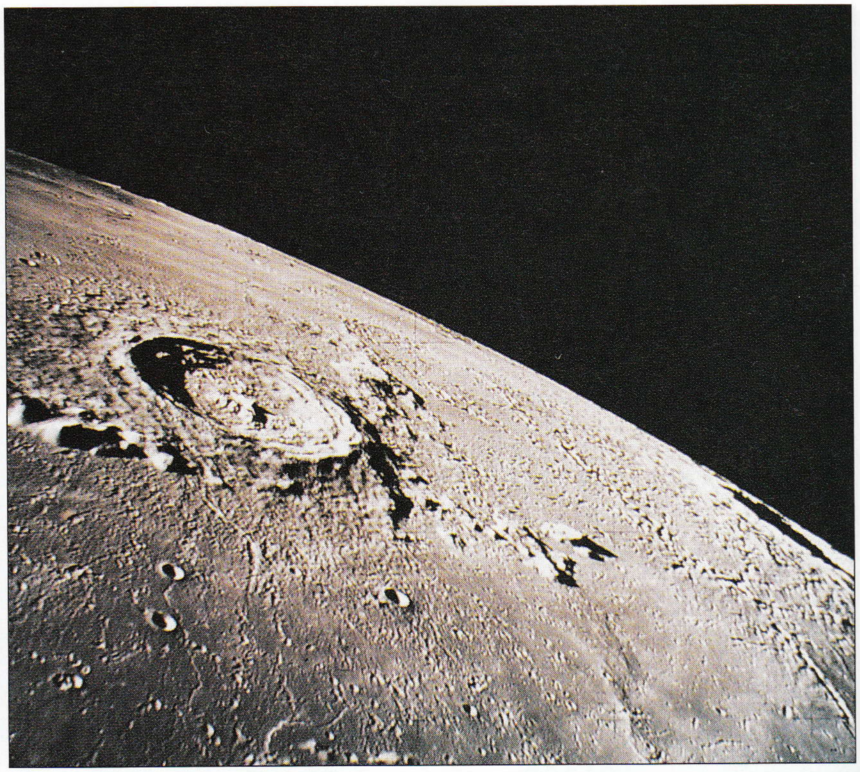


FIGURE 6.6
Central peak in a crater and slumped inner walls. Apollo astronauts took this photograph of the crater Eratosthenes on the last manned flight to the Moon. This crater is 58 kilometers (approximately 36 miles) in diameter.
(Courtesy of NASA.)

Astronomers believe the maria are also impact features, but to understand their formation, we must briefly describe the early history of the Moon. From the great age of the highland rocks (in some cases as old as 4.5 billion years), astronomers deduce that these rugged uplands formed shortly after the Moon's birth. At that time, the Moon was probably molten, allowing heavier (dense), iron-rich material to sink to its interior while lighter (less dense) material floated to the lunar surface. On reaching the surface, the less dense rock cooled and congealed, forming the Moon's crust. A similar process probably formed the Earth's continents. The highlands were then heavily bombarded by solid bodies from space, forming the numerous craters we see there.

As the Moon continued to cool, its crust thickened. But before the crust grew too thick, a small number of exceptionally large bodies—objects over 100 kilometers (about 60 miles)—struck the surface, blasting huge craters and pushing up mountain chains along their edges, as you can see in figure 6.7. Subsequently, molten material from deep within the Moon gradually flooded the vast crater and congealed to form the smooth, dark lava plains that we see now. Because the denser material sunk to the Moon's interior during its molten stage, the erupted lava from those depths was denser than the crustal rock into which it flooded. Moreover, because it was molten more recently, the mare material is therefore younger than the highlands. By the time the maria formed, most of the impacting bodies were gone—collected into the Earth and Moon by earlier collisions. Thus, too few bodies remained to crater the maria, which therefore remain smooth, even to this day.

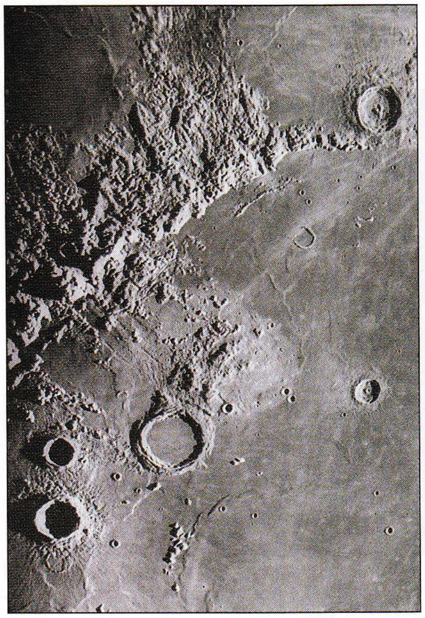


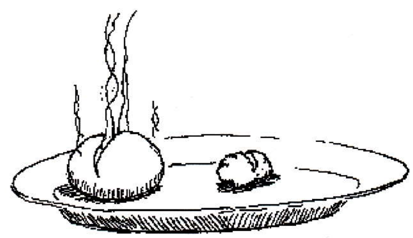
FIGURE 6.7
Photograph of mountains along the edge of a mare. These mountains were probably thrown up by the impact that created the mare.
(© UC Regents; UCO/Lick Observatory image.)

Our home planet Earth furnishes additional evidence that most lunar craters formed early in the Moon's history. Like the Moon, Earth too was presumably battered by impacts in its youth. Although the vast multitude of these craters have been obliterated by erosion and plate tectonics, a few remain in ancient rock whose measured age is typically hundreds of millions of years. From the scarcity of such craters, astronomers can deduce that the main bombardment must have ended billions of years earlier.

Craters and maria so dominate the lunar landscape that we might not notice the absence of folded mountain ranges and the great rarity of volcanic peaks, land forms common on Earth. Why have such features not formed on the Moon?

6.2 STRUCTURE OF THE MOON

The Moon's small size relative to the Earth explains the differences between the two bodies. We saw in chapter 5 that radioactive elements in the Earth's interior heat it. The Moon is also heated by radioactive material, but because its volume compared to its surface area is small relative to the Earth's, heat escapes far more easily from the Moon. Thus, the Moon has cooled far more than the Earth. (Think of how a small baked potato cools much faster than a big one.) Moreover, because its mass is much smaller than the Earth's, the Moon contains much less radioactive material and so cannot generate as much heat. Thus, without a strong heat source, the Moon lacks the convection currents that drive plate tectonic activity on the Earth. Confirmation of this comes from studies of the Moon's interior.



(Courtesy of Peter Arnold.)

Crust and Interior

The Moon's interior can be studied by seismic waves just as the Earth's can. One of the first instruments set up on the Moon by the Apollo astronauts was a seismic detector. Measurements from that and other seismic detectors placed by later Apollo crews show that the Moon's interior is essentially inactive and has a much simpler structure than the Earth's.

Footprint of an astronaut on the Moon.
(Courtesy of NASA.)

The Moon's surface layer is shattered rock that forms a **regolith**—meaning "blanket of rock"—tens of meters deep. The regolith consists of both rock chunks and fine powder, the result of successive impacts breaking rock into smaller and smaller pieces. This powdery nature is easily seen in the crispness of the astronauts' footprints. Samples of the regolith picked up by astronauts show that these surface rocks are typically the same type as the underlying rock. That is, the regolith on maria is generally basaltic, whereas that on the highlands is anorthositic. In places the regolith may extend several hundred meters below the surface. Analysis of the regolith shows that over time, its rocks have been broken up by high-velocity impacts, supporting the interpretation that the surface has been bombarded by meteoritic bodies.

Below this surface layer of rocky rubble is the Moon's crust, about 100 kilometers (60 miles) thick, on the average. The crust is much thinner (about 65 kilometers) on the side of the Moon that faces the Earth than on the far side, but the reason for this difference is not clear. It may result from the Earth's gravity shifting the Moon's core slightly toward Earth billions of years ago, when the Moon's interior was hotter. The crust on the near side—being slightly closer to the Moon's core because of that shift—might therefore have become hotter and as a result thinner than that on the far side. Subsequently, the Moon cooled, leaving the crust thinner on one side than the other. The thinner crust on the near side made it much easier for maria to form, as you can see in figure 6.8.

The Moon's crust, like the Earth's, is composed of silicate rocks relatively rich in aluminum and poor in iron. Beneath the crust is a thick mantle of solid rock, extending down about 1000 kilometers (600 miles). The Moon's mantle is probably rich in olivine, the same type of dense, greenish rock that composes most of the Earth's mantle. Unlike the Earth's mantle, however, it appears too cold and rigid to be stirred by the Moon's feeble heat.

The Moon's low density (3.3 grams per cubic centimeter) tells us its interior contains little iron. Recall how in chapter 5 we saw that the Earth's high density (about 5 grams per cubic centimeter) was an indication that it had a large iron core. Some

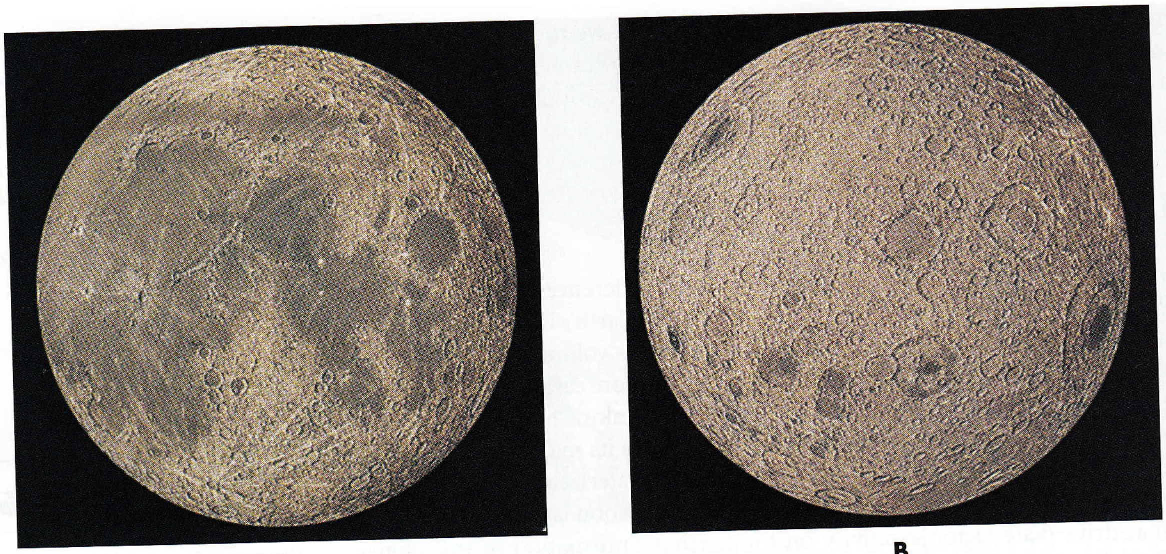


FIGURE 6.8
(A) The near side of the Moon and (B) the far side. Note how uncommon maria are on the far side.
(Courtesy of NASA/National Geographic Society.)

Question: Why can't we see the far side of the Moon from Earth?

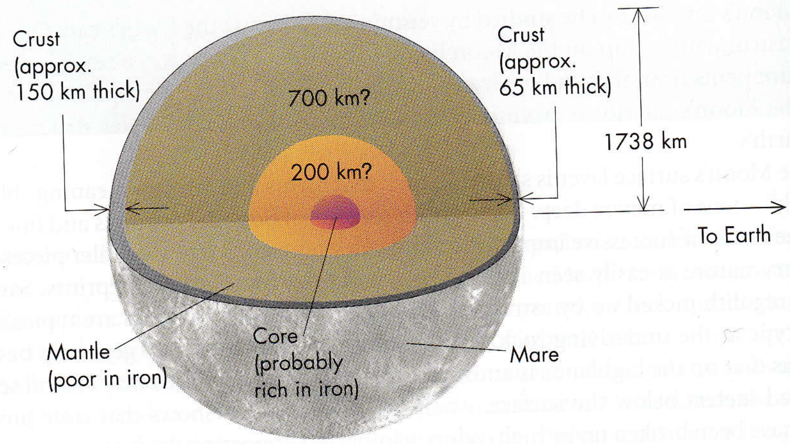


FIGURE 6.9
An artist's impression of the Moon's interior. Notice the thinner near-side crust and the displacement (exaggerated for clarity) of the core toward the Earth.

Lunar scientists have found tiny quantities of gas, mostly helium, above the Moon's surface. This gas is so tenuous (less than one-quadrillionth the density of our atmosphere) that we will ignore it. Perhaps more interesting, however, is the detection of traces of hydrogen near the Moon's poles by a spacecraft orbiting the Moon. Some scientists think the hydrogen comes from the breakdown of frozen water mixed with rock in several craters near the lunar poles. The water itself may have come from comets striking the Moon and vaporizing. The water vapor then condensed in the coldest places on the Moon (the polar craters into which sunlight never shines). You may have seen this tendency for frost to form in cold spots if you have taken something out of a freezer and left it for a while on a table.

molten material may lie below the mantle, as illustrated in figure 6.9, but the Moon's core is smaller and contains far less iron and nickel than the Earth's. These factors, plus the Moon's slow rotation, lead astronomers to think that the Moon's core is unable to generate a magnetic field as the Earth does. Measurements made by the Apollo astronauts confirm that the Moon has essentially no magnetic field. Thus, a compass would be of no use to an astronaut lost on the Moon.

The Absence of a Lunar Atmosphere

The Moon's surface is never hidden by lunar clouds or haze, nor does the spectrum of sunlight reflected from it show obvious signs of gases. With no atmosphere to absorb and trap heat, temperatures on the Moon soar during the day and plummet at night. Likewise, no wind blows, and so the lunar surface lies dead and silent under a black sky.

The Moon has no atmosphere for two reasons. First, its interior is too cool to cause volcanic activity, which as we saw in chapter 5 was probably the source of much of the Earth's early atmosphere. Second, and more important, even if volcanos had created an

atmosphere in its youth, the Moon's small mass creates too weak a gravitational force for it to retain the erupted gas. In chapter 2, we learned that the Moon's escape velocity is only about a fourth that of the Earth's (2.4 kilometers per second versus 11 kilometers per second), and so atoms in the Moon's atmosphere would have found it easy to escape its gravity. With no atmosphere and no plate tectonics, the Moon has been essentially unchanged for billions of years. The footprints left on the Moon by the astronauts in 1969 will probably still be there a million years from now.

6.3 ORBIT AND MOTIONS OF THE MOON

By watching the Moon for a few successive nights, you can see it move against the background stars as it follows its orbit around the Earth. The Moon's orbit is elliptical, with an average distance from Earth of 380,000 kilometers (about 250,000 miles) and a period of 27.3 days.* Its distance can be measured by triangulation, radar, or laser beams (fig. 6.10). To triangulate its distance, astronomers observe the Moon from two different spots on the Earth. The distance between the locations, the angles to the Moon, and a little trigonometry give the Moon's distance.

A more accurate method is to bounce either a radar pulse or a laser beam off the Moon. Half the time interval between the transmission and the return of the reflected radiation multiplied by the speed of light gives the Moon's distance to an accuracy of centimeters.

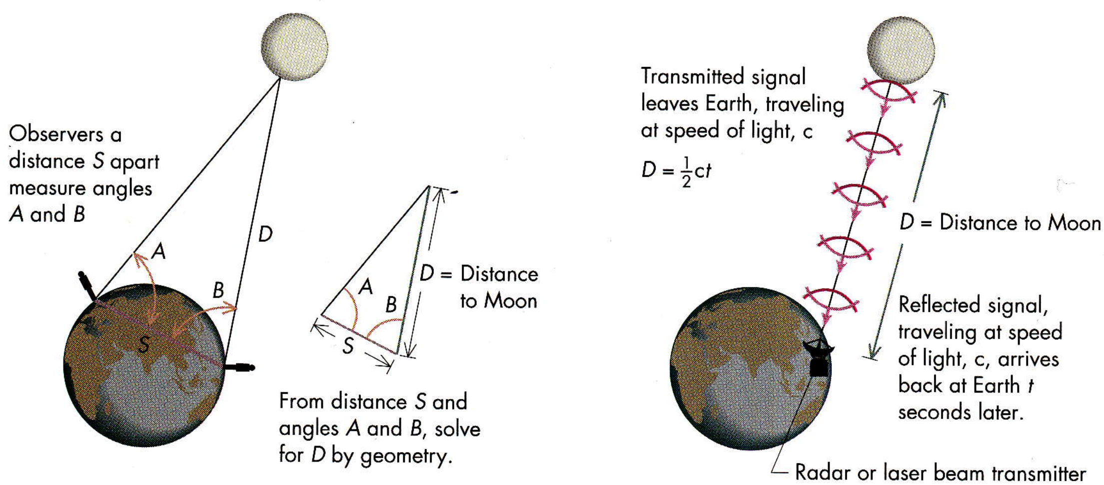
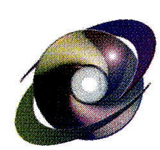


FIGURE 6.10
Finding the distance from the Earth to Moon by triangulation and radar and laser ranging.

The Moon's Rotation

As it orbits, the Moon keeps the same side facing the Earth, as you can see by watching it through a cycle of its phases. You might think from this that the Moon does not rotate. Figure 6.11 shows, however, that the mountain on the side facing the Earth points to the right when the Moon is at A and to the left when the Moon is at B. Thus, the Moon *does* turn on its axis but with a rotation period exactly equal to its orbital period, a condition known as **synchronous rotation.** The Earth's gravity causes this locking of the Moon's spin to its orbital motion, as we will discuss in section 6.6.



The rotation of the Moon

*This is the time to complete an orbit around the Earth and is shorter than the cycle of the phases, as discussed in chapter 1.

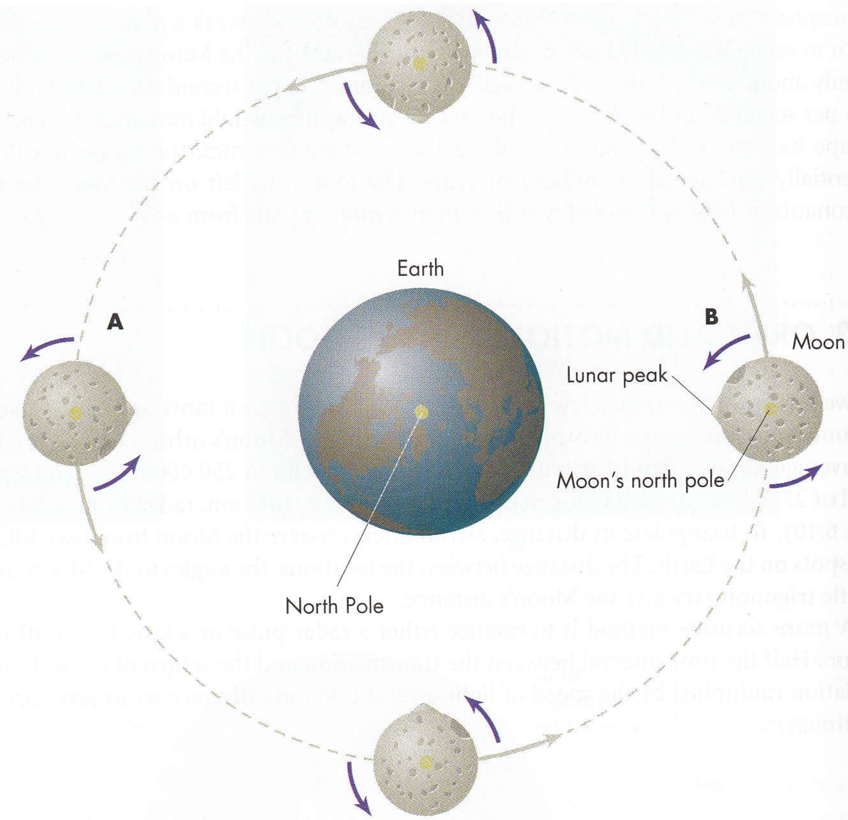


FIGURE 6.11
The Moon rotates once each time it orbits the Earth, as can be seen from the changing position of the exaggerated lunar mountain. Notice that at (A) the lunar peak is to the right, while at (B) it is to the left. Thus, from the Earth, we always see the same side of the Moon even though it turns on its axis.

To help see that the Moon rotates even though it keeps the same face toward the Earth, put a coin on the figure of the Moon and move it around the Earth so that the same edge of the coin always faces the Earth.

FIGURE 6.12
The Moon's orbit is tipped 5° with respect to the Earth's. The angle is exaggerated for clarity.

Oddities of the Moon's Orbit

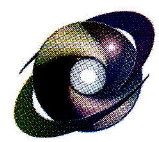
The Moon's orbit is tilted by about 5° with respect to the Earth's orbit around the Sun, as illustrated in figure 6.12. It is also tilted with respect to the Earth's equator and is thus unlike most of the moons of Jupiter, Saturn, and Uranus, which lie nearly exactly in their planets' equatorial plane. These oddities indicate that our Moon formed differently from the moons of other planets, a conjecture supported by the odd mass ratio of the Earth and Moon.

Most moons are tiny compared with their planets. Even the largest of the moons of Jupiter and Saturn have masses less than 1/1000 that of their planet. But our Moon's mass is 1/81 that of the Earth's. Why is our Moon so different in its mass and orbit from the moons of other planets?

6.4 ORIGIN AND HISTORY OF THE MOON

Lunar rocks brought back to Earth by the Apollo astronauts have led astronomers to radically revise their ideas of how the Moon formed. Before the Apollo program, lunar scientists had three hypotheses of the Moon's origin. In one, the Moon was originally a small planet orbiting the Sun that approached the Earth and was captured by its gravity (capture theory). In another, the Moon and Earth were "twins," forming side by side from a common cloud of dust and gas (twin formation theory). In the third, the Earth initially spun enormously faster than now and formed a bulge that ripped away from the Earth to become the Moon (fission theory).

Each of these hypotheses led to different predictions about the composition of the Moon. For example, had the Moon been a captured planet, its composition might be very unlike the Earth's. If the Earth and Moon had formed as twins, their overall composition should be similar. Finally, if the Moon was once part of the Earth, its composition should be nearly identical to the Earth's crust. When the rock samples were analyzed, astronomers were surprised that for some elements, the composition was the same, but for others, it was very different. For example, the Moon has a relatively high abundance of high-melting-point materials such as gold and an almost complete lack of low-melting-point materials such as water. It also has much less iron than the Earth, as we pointed out when discussing its interior and low density.



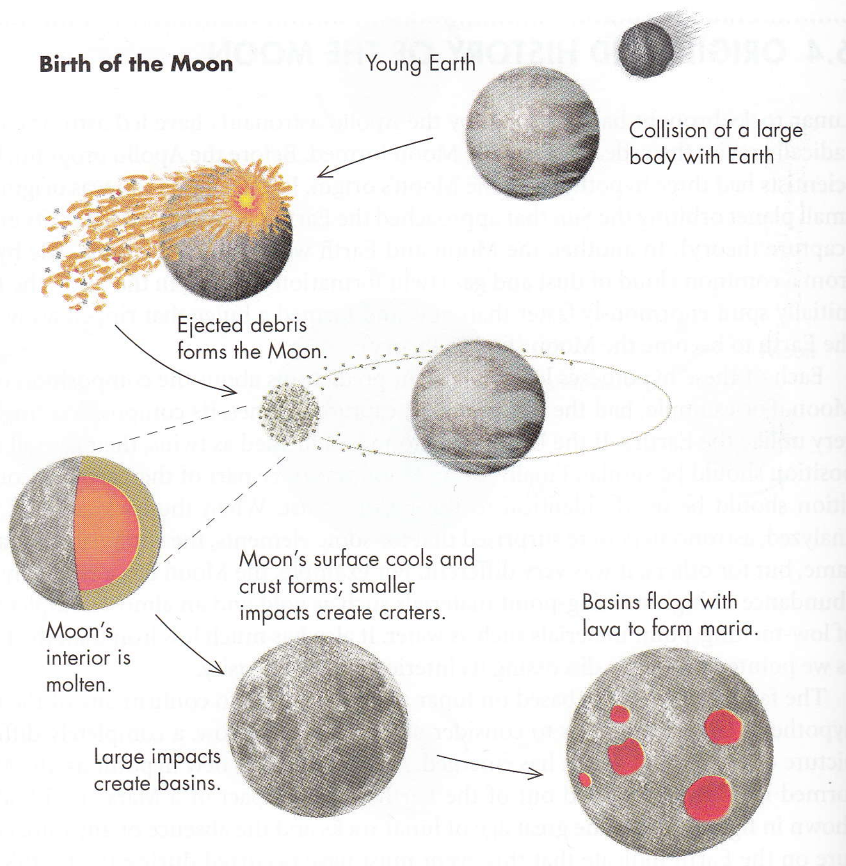
The birth of the Moon

The failure of evidence based on lunar surface samples to confirm any of the three hypotheses led astronomers to consider alternatives, and now, a completely different picture of the Moon's origin has emerged. According to the new hypothesis, the Moon formed from debris blasted out of the Earth by the impact of a Mars-sized body, as shown in figure 6.13A. The great age of lunar rocks and the absence of any impact feature on the Earth indicate that this event must have occurred during the Earth's own formation, at least 4.5 billion years ago. The colliding body melted and vaporized millions of cubic kilometers of the Earth's surface rock and hurled it into space in an incandescent plume. As the debris cooled, its gravity gradually drew it together into what we now see as the Moon.

This violent birth hypothesis explains many of the oddities of the Moon. The impact would vaporize low-melting-point materials and disperse them, leaving, for example, little water to be incorporated into the lunar body. Computer models (fig. 6.13B) of such an event also show that only surface rock would be blasted out of the Earth, leaving our planet's iron core intact, thereby also explaining the low iron content of lunar rocks. The splashed-out rock would condense in an orbit whose shape and orientation were determined by the collision rather than by the orientation of the Earth's equator. Furthermore, we would expect both similarities and differences in composition between the Earth and Moon because the Moon was made partly from Earth rock and partly from rock of the impacting body. A bonus of the hypothesis is that it explains why the Earth's rotation axis is tipped so much more than the rotation axis of Mercury, Venus, or Jupiter: the impact knocked the Earth part way over.

After the Moon's birth, stray fragments of the ejected rock pelted its surface, creating the craters that blanket the highlands, as depicted in figure 6.14. A few huge fragments plummeting onto the Moon later in its formation process blasted enormous holes that later flooded with molten interior rock to become the maria. That rock was probably melted in the Moon's interior by radioactive decay, as happened in the Earth. During the time it took the rock to melt, about half a billion years, most of the debris remaining in the Moon's vicinity fell onto its surface. Thus, by the time the maria flooded, little material was left to fall on them, and so they are only lightly cratered. Since that time, the Moon has experienced no major changes. It has been a virtually dead world for all but the earliest times in its history, but it nevertheless creates effects on Earth: eclipses and tides.

FIGURE 6.13
(A) The birth of the Moon. (B) This computer simulation 1–4 shows how the Moon might have formed when a Mars-sized body hit the young Earth and splashed out debris that later assembled into the Moon. The scale changes between the frames: (1) is a close-up of the impact; (4) shows the newly assembled Moon (lower left) orbiting the Earth, which is still surrounded by debris.
(Courtesy of A. G. W. Cameron, Lunar and Planetary Laboratory, University of Arizona.)



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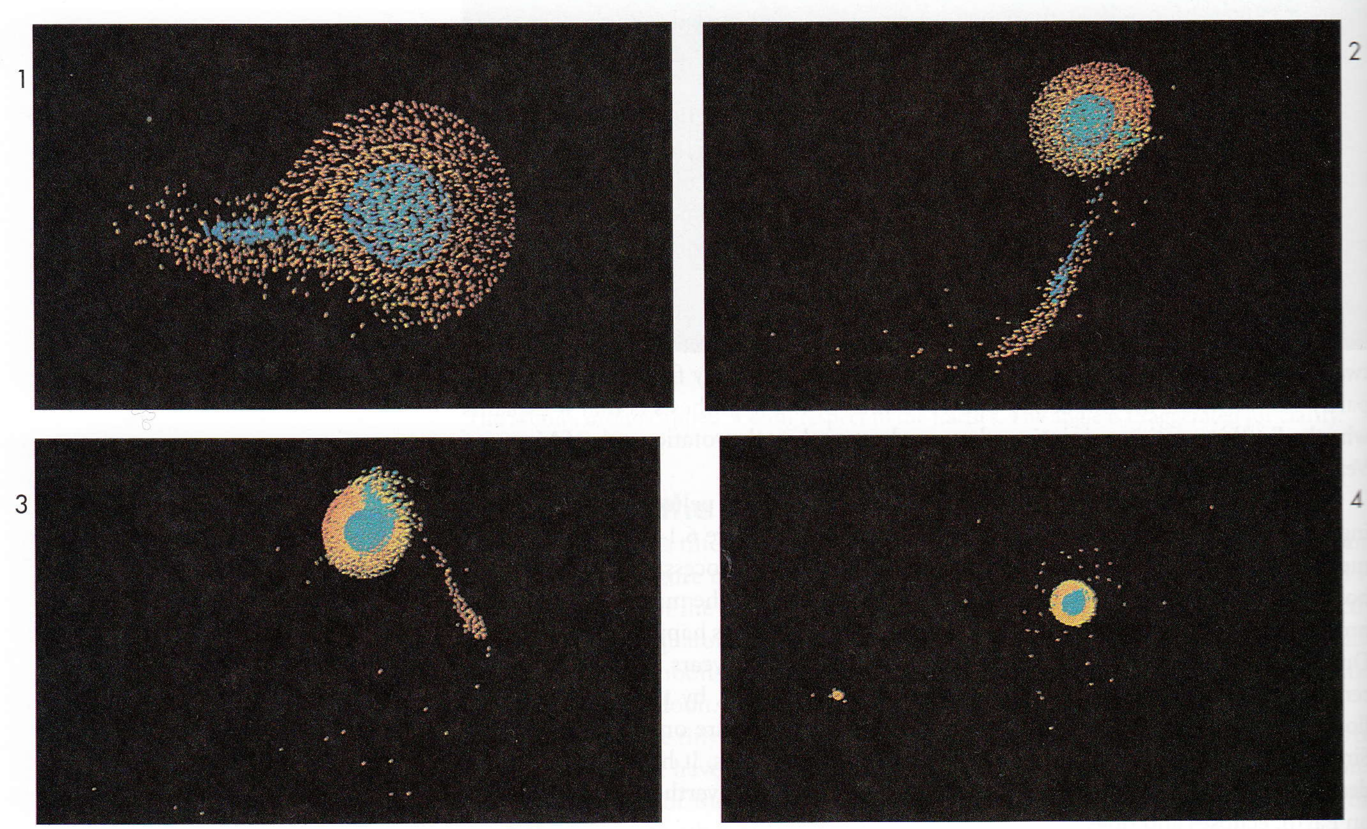

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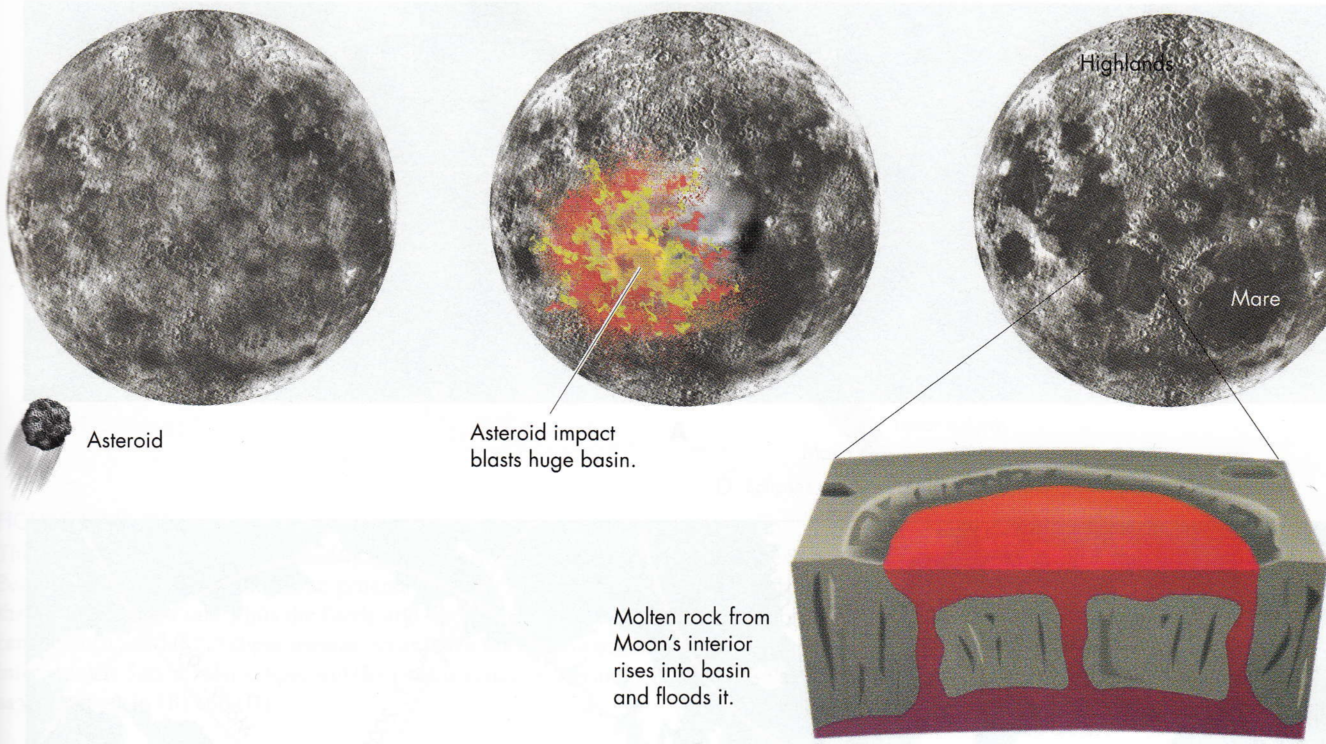

FIGURE 6.14
A rain of debris creates craters on the young Moon. Large impacts late in the process form the maria basins. Lava floods the basins to make the maria.

6.5 ECLIPSES

An **eclipse** occurs when one astronomical body casts its shadow on another. As discussed in chapter 1, for us on the Earth two types of eclipses can occur: lunar and solar. A lunar eclipse happens when the Earth's shadow falls on the Moon. A solar eclipse happens when the Moon's shadow falls on the Earth. The great beauty of eclipses and their rarity make them eagerly awaited, and table 6.1 lists some upcoming ones. The approximate locations of the tabulated solar eclipses are shown in figure 6.15B.

TABLE 6.1
Some Upcoming Solar and Lunar Eclipses

Solar Eclipses		Lunar Eclipses	
Dec 4, 2002	Southern Africa, Australia	May 16, 2003	Antarctica, most of Africa and Europe, most of the Americas
Nov 23, 2003	Antarctica, extreme south of South America	Nov 8/9, 2003	Most of Asia, Africa, Europe, The Americas except extreme SW Alaska
March 29, 2006	North-central Africa, Turkey, and Southern Russia	May 4, 2004	Antarctica, Australia, Indonesia, most of Asia, Africa, most of Europe, eastern South America